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THE DEPLETION OF GROUND-WATER SUPPLIES[1]

By Robert E. Horton[2]

Time required for a well to reach equilibrium with constant draught. It not infrequently occurs where wells are used for public water supply or for irrigation that there is a progressive depression of the water table, sometimes continuing for years. It is evident that a new well might derive an initially large but ever decreasing supply from connate water, even with no infiltration. In general, with constant draught and infiltration, the well will reach equilibrium when

Total inflow + Storage draught = Total draught.

For a horizontal or nearly horizontal water table, the inflow takes place by infiltration over the cone of depression created by the well. If the slope of the cone of influence is known, then the radius and volume of the cone for any depth of depletion, and the area over which infiltration supples the well at any moment can be determined. Miller-Brownlie[3] has attacked this problem at a different angle from other investigators. Instead of assuming, as is often done, a constant maximum radius of the cone of influence, he assumes a minimum constant slope of the water table within the limits of the cone, which slope he assumes will be quickly reached after pumping begins and will remain constant as depression advances. He says:

> Observations made during the past few years of the subsoils of the Punjab have shown that the slopes necessary to cause water motion have varied from 1 in 260 in moderately coarse sand to 1 in 175 for fairly fine sand. In gradients flatter than this in each type of sand there is no apparent motion. Capillary attraction interferes with the true flow, and investigation into the forward motion becomes greatly involved. Observations indicate that any lateral or forward motion of water, where the hydraulic gradients are slightly less than those mentioned, is so slow that for practical purposes it may be neglected, the actual velocity probably not exceeding a few inches per day.

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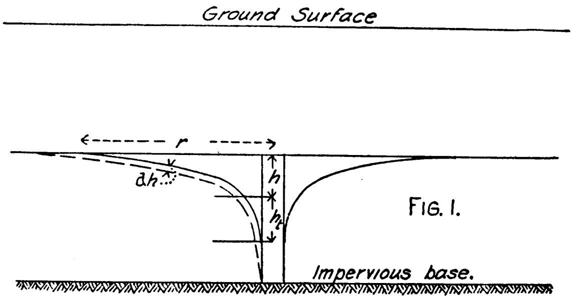
[3] "Subsoil Water in Relation to Tube Wells for Irrigation," *Engineering and Contracting*, March 31, 1920, page 355.

In effect this amounts to the assumption that there is a minimum angle of friction for ground water similar to the angle of friction for solids. If the slope of the water table is at less than this minimum angle, motion, or at least appreciable motion, in supplying a well, will not occur.

Miller-Brownlie applies this principle to the determination of the progressive depletion of wells, making computations by yearly intervals.



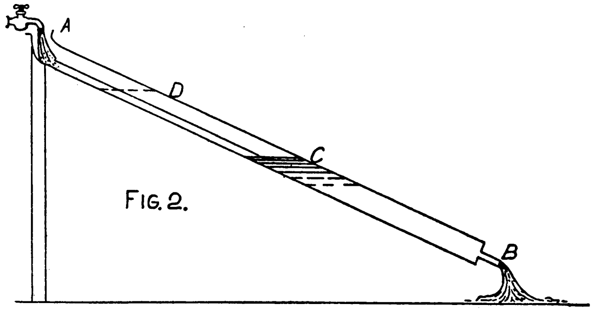


FIG. 1. CONDITIONS ADJACENT TO A PUMPED WELL

FIG. 2. SHRINKAGE OF ARTESIAN AREA WITH INCREASED DRAUGHT OF WATER

The same results may be obtained by the use of a general formula derived as follows: Referring to figure 1, let

r = radius of cone of influence at time t in years;
m = assumed minimum slope for the given soil;
h = the true or cone depression of the water table at the well, due to the slope of the water table.

This is designated by Miller-Brownlie as the "vertex head." This does not include the abrupt depression h_t due to entrance resistance immediately around the well, which may amount to a few feet. This is designated by Miller-Brownlie as the "trumpet head," from the resemblance of the form of depression at the well to the mouth of a trumpet.

$h = mr$ and
$H = h + h_t$ = total depression.
P = available porosity of the medium.
I = Infiltration depth inches on surface per year.
F = Infiltration rate at time t, cubic feet per year.
Q = Rate of draught or pumpage, cubic feet per year.
q_g = Rate of draught or pumpage, millions of gallons per 24 hours.
S = Total storage depletion in cubic feet at time t.

Then in units of cubic feet per year:

$$S = \frac{\pi P}{3} m^2 r^3 \qquad (1)$$

$$F = \frac{I}{12} \pi r^2 \qquad (2)$$

The limit of the cone of influence for constant pumping will be reached when $F = Q$, or when

$$r = \sqrt{\frac{12\,Q}{\pi I}} \text{ or } h_c = m\sqrt{\frac{12\,Q}{\pi I}} \qquad (3)$$

To determine the time when this limit will be reached, or when any less depletion will be reached, it is necessary to solve the storage equation

Inflow = Outflow + Gain or − Loss of storage.....(4)

For an increment of time dt, during depletion, the loss of storage is the difference of volume of porosity in two cones of altitudes h and h + dh respectively, and side slopes m. This is very approximately equal to the convex surface of a cone of base radius r and altitude h, or πr^2 sec. A multiplied by $P\cos A\,dh$ or

$$dS = P\pi r^2 dh \qquad (5)$$

Substituting (2) and (5) in (4) for time dt,

$$\frac{I}{12}\pi r^2 dt = Q dt - P\pi r^2 dh \qquad (6)$$

But $r = h/m$

$$\text{Let } A = \frac{I\pi}{12\,m^2} \qquad B = \frac{P\pi}{m^2} \quad \ldots\ldots\ldots\ldots\ldots (7)$$

$$Ah^2 dt = Q dt - Bh^2 dh \quad \ldots\ldots\ldots\ldots\ldots\ldots (8)$$

Divide by dt and transpose –

$$dt = \frac{Bh^2}{Q - Ah^2}\, dh \ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

This can be integrated by known forms, giving

$$t = 2.30\,\frac{BQ}{2\,A\sqrt{AQ}}\,\log_{10}\frac{\sqrt{Q} + h\sqrt{A}}{\sqrt{Q} - h\sqrt{A}} - \frac{Bh}{A} \quad \ldots\ldots (10)$$

Miller-Brownlie's treatment of this subject, and the author's formula based thereon, differ from the usual mode of treatment in that it is assumed that the supply of the well is ultimately derived entirely from infiltration over the area covered by the cone of influence, whereas in the usual method of treatment heretofore it is assumed that the well is supplied by water flowing into the cone of influence around the periphery of this cone, and infiltration on the area of influence is neglected. The usual formulas give the yield of the well in terms of the depth of depression of the water table. The author's formula not only gives the ultimate depth of depression which is approached as a limit as pumping continues, but it will also give the depression of the water table at the well at any chosen time interval after pumping begins.

Inspection of the formula shows that the value of t becomes infinity when the denominator of the logarithmic term becomes zero, that is when

$$\sqrt{Q} = h\sqrt{A} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (11)$$

or when

$$h = \sqrt{\frac{Q}{A}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (12)$$

This is the limit of the vertex head, and this formula gives the same result as that obtained by the solution of equation (3). In the example given herewith, the limiting depression approaches 33.68 feet. Table 1 contains the results of a solution of equation (10) for a well used as an example to illustrate the method by Miller-Brownlie. The results agree substantially with those obtained by Miller-Brownlie by solution for successive finite increments of h.

TABLE 1

Calculation of Depletion of Ground Water in a Well for $Q = 3$ *c.f.s.* $I = 0.8$ *ft. per Year.* $M = 0.00555$ *and* $P = 0.30$ *where*

$$t = 14.54 \text{ Log.}_{10} \frac{9\,592 + 285h}{9592 - 285\,h} - 0.375\,h.$$

h_c	285 h_c	9592 + 285 h_c	9592 − 285 h_c	COL. (3) ÷ COL. (4)	LOG. COL. (5)	14.54 × COL. (6)	0.375 h_c	t=COL. (7) − COL. (8). YEARS
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
5	1,425	11,017	8,167	1.348	0.12969	1.88	1.87	0.01
10	2,850	12,442	6,742	1.845	0.26600	4.10	3.75	0.35
15	4,275	13,867	5,317	2.608	0.41631	6.03	5.62	0.41
20	5,700	15,292	3,892	3.928	0.59417	8.61	7.50	1.11
25	7,125	16,717	2,467	6.78	0.83123	12.04	9.38	2.66
28	7,980	17,572	1,612	10.89	1.03703	15.08	10.50	4.58
30	8,550	18,142	1,042	17.42	1.24080	17.98	11.25	6.73
31	8,835	18,427	757	24.35	1.38650	20.16	11.62	8.54
32	9,120	18,712	472	39.65	1.59824	23.20	12.00	11.20
33	9,405	18,997	187	101.50	2.00647	29.08	12.38	16.70
33.5	9,547.5	19,140	45.5	421.00	2.62428	38.04	12.56	25.48

Let $Q = 3$ c. f. s. = 92,016,000 cu. ft. per year.

$I/12 = 0.8.$ $P = 0.30.$ $m = \frac{1}{180} = 0.00555.$

$\frac{1}{m} = 180.$ $\frac{1}{m^2} = 32{,}400.$

$A = 0.8 \times \pi \times 32{,}400 = 81{,}389.$

$B = 0.3 \times \pi \times 32{,}400 = 30{,}521.$

$B/A = 3/8 = 0.375.$

$\sqrt{Q} = 9591.7.$

$\sqrt{A} = 285.$

$\sqrt{AQ} = 2{,}733{,}720.$

$2\sqrt{AQ} = 5{,}467{,}440.$

$Q/2\sqrt{AQ} = 16.83.$

$$t = 14.54 \log_{10} \frac{9592 + 285h}{9592 - 285h} - 0.375\,h.$$

In this example a depletion of nearly 20 feet occurs in the first year because the infiltration area is naturally small, and the supply is at first drawn mainly from ground-water storage. After the first few years the infiltration rate approaches the draught rate, and the depletion approaches the limit 33.68 feet more and more gradually as time goes on.

If a well is put down in the surface ground water horizon, and this is underlain by an impermeable stratum, then the maximum draught from the well will be that for which the depression of the vertex head plus the trumpet head equals the depth of the ground water. Until this depression is attained a greater rate of pumping can be carried on. Formula (3) is therefore adapted to the determination of the maximum yield which can be permanently derived from a given well. For this purpose it takes the form

$$Q = \frac{\pi I}{12}\left(\frac{H_g - h_t}{m}\right)^2 \ldots\ldots\ldots\ldots\ldots\ldots (13)$$

in which H_g is the total depth of ground water. The trumpet head h_t is the only factor that varies with the diameter of the well. For a given draught rate, this varies about inversely as the circumference of the bore.

For example, with the other factors the same as before, $H_g = 20$ feet, and $h_t = 5$ feet, $Q = 18{,}300{,}000$ cubic feet per year, or 33,400 gallons per day, a comparatively small yield, because of the limited area of infiltration tributary to the well. This shows the importance of a deep ground water bed as affecting the yield of a well in the surface zone of ground water. The formula has limitations in its applicability to a well penetrating a definite vein of free flowing ground water, in which case m is practically zero.

If a well is put down into a ground-water horizon in a deep permeable stream, the surface of the water table being nearly flat, but there being a gradual flow or drift in one direction, then it is evident that water will flow into the cone of depression from one side, and a nearly equal amount will flow out from the opposite side. The effect will be to distort the form of the area of depression making it eccentric to the well, with the shorter radius on the upstream and longer on the downstream side, but without much influence on the yield of the well. In fact, it is evident that if a series of uniformly spaced wells was put down and pumped at such rates that their cones of influence were tangential circles, then the supply to each well would be derived necessarily from infiltration over the area of influence.

The Miller-Brownlie formula applies directly to this case, whereas the ordinary formulas are inconsistent in that they assume in such a case that the well is supplied from the area between the tangential cones of influence, in spite of the fact that at the points where the circles of influence are tangential there is no infiltration whatever.

Depletion of artesian basins. The matter here considered is entirely distinct from the reduction in flow of artesian wells by mutual interference of wells spaced too closely. An artesian basin may have a capacity so great that the pressure over the basin as a whole is not materially affected by a limited number of wells, but if two or more wells are spaced too closely, cones of pressure reduction adjacent to the wells will overlap, and the supply available from each well will be reduced.

On the other hand, a large number of wells distributed over a basin, and so spaced as to avoid mutual interference, may gradually deplete the artesian supply to such an extent that some of the wells, usually those at higher elevations or nearest the intake beds, will cease to flow. This condition has developed notably in some of the great artesian basins of Australia, and in Southern California.

It is convenient here to consider artesian basins of four kinds:

(1) Inclined basins with ocean outlets.

(2) Inclined or saucer-shaped basins with outlets through artesian springs only.

(3) Inclined or saucer-shaped basins without natural outlets.

(4) Buried or imbedded artesian basins.

The various artesian horizons adjoining the Gulf of Mexico in Southern Texas afford illustrations of the first type. Here, before wells were bored, a balance was maintained between the inflow to the basin through the intake beds, and the outflow where the beds are exposed beneath the sea level, by slight fluctuations in the volume of storage in each artesian horizon.

The conditions are illustrated by figure 2. The pipe *AB* corresponds to the water-bearing beds. As long as the outlet at *B* remains unchanged in size, the water level at *D* will fluctuate only to such an extent as is required to satisfy the storage equation

$$\text{Inflow} = \text{Outflow} \begin{pmatrix} + \text{ Gain or} \\ - \text{ Loss of Storage.} \end{pmatrix}$$

If in addition to an outlet at *B*, wells are put down along the line *DB*, affording additional outlets, then a less head will be required to discharge a quantity of water equal to the inflow at *A* and the ground-water horizon adjacent to the intake will fall to some level lower than *D*. As the flow of wells is increased between *A* and *D*, the pipe will not be filled with water and a well put down in this region will have no pressure in excess of that of the atmosphere. As the number of wells between *D* and *A* is increased, the static water level in the ground-water horizon on the intake side of the basin will further recede, the artesian pressure over the entire basin will be decreased, and if the number of outlets is sufficient, the artesian horizon will fall to some level *C*, and wells located between *D* and *C* will cease to flow, while these between *C* and *B* will continue to flow but under greatly reduced heads.

It is evident from these considerations that excessive draught from an artesian basin in general has the effect of reducing the artesian area on the side of the basin located nearest the intake beds. Precisely this result has followed excessive pumping from the artesian basin of Los Angeles County, Cal., illustrated by figure 3, where the intake beds lie to the northeast. In such cases the depletion of the artesian horizon and the reduction in the artesian area may be very gradual, if the basin is large, owing to the fact that during the period of depletion to a given level the available supply equals the simultaneous inflow plus the water previously stored in the water-bearing beds of the depleted area.

Reverting to figure 2, the available supply during depletion from level *D* to level *C* equals the inflow plus the initial storage in the prism *DC*, when saturated, minus the limited volume of water remaining in this prism after depletion of the water horizon to the level *C*.

The lower peninsula of Michigan apparently affords examples of large saucer-shaped artesian basins, in which the natural outflow was through artesian springs in the river valleys. The conditions governing the depletion of artesian areas without ocean outlets are the same as for inclined basins with ocean outlets, but the effect may be somewhat more complicated.

Sealed artesian basins of type 3, for which there are no natural outlets, the water remaining stagnant until the wells are put down, are probably rare in occurrence and usually of limited extent. Such a basin having no natural outlets may, if tapped by a bore, yield at first a large supply of water, but if, as is likely to be the case, the storage in the water-bearing beds and the intake area are limited, the available supply and the artesian head may decrease rapidly.

It is possible that such an artesian bed may have been saturated with salt or connate water, and the effect of an artesian bore in such a basin may be the production of a well from which the salt or other

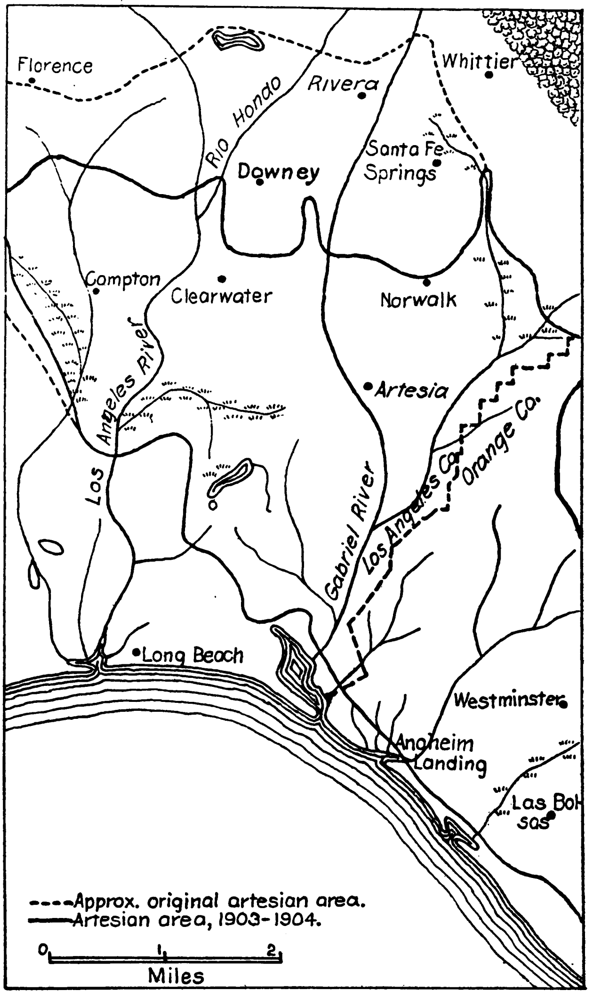


FIG. 3. DOWNEY ARTESIAN AREA, CALIFORNIA

mineral constituents of the water will gradually decrease as the original stagnant water is replaced by fresh water taken in through the intake beds.

Obviously, an artesian horizon without natural outlets, but with an intake bed, would fill up to the surface level at the intake beds. The intake beds in such a case would probably be permanently or intermittently moist or swampy. The draught of water from the basin through artesian bores would have a tendency to drain the swampy intake area. There is some evidence that a few instances of this kind may have occurred in the case of shallow artesian horizons underlying the deposits of glacial drift in Southern Michigan.

It is of course possible that beds of porous material laid down in the bottoms of shallow fresh-water lakes, and around their margins, may be covered with impervious materials while saturated, in such a manner as to be completely sealed, leaving no outlet nor permeable intake area. An inclined bed of porous material bearing connate water, but without an intake area, would, if tapped by a bore under suitable conditions, afford a yield of artesian water which might be fresh but would probably be highly mineralized. Theoretically, at least, air must enter the bed before water can flow out, unless the bore reaches the ground surface at a level more than 34 feet below the uppermost water surface level in the water-bearing bed. However, more or less air and other gases are always contained in the pores of even the most impervious rocks, and air will flow through openings which water will not enter, so that a bed of connate water such as described, and which represents virtually a fossil lake, may yield at first a liberal supply of artesian water. Having no intake supply the flow from the well will rapidly decrease and soon cease, and the supply cannot be replenished.

In the case of artesian basins of the first three types mentioned, having intake beds, the original conditions can be restored after depletion by a cessation of draught from the wells sufficient to restore natural equilibrium by filling up the water-bearing beds to their initial level. It is important to note that repletion occurs only when the inflow exceeds the draught. A reduction of the draught rate to the equivalent of the inflow rate after the artesian horizon is depleted affords no remedy. An equal quantity of water can be drawn from the same basin continuously under greater heads, over a larger area, and in larger volumes per individual well, if the original conditions of equilibrium are restored.

For example, the artesian basins of Los Angeles County, Cal., may be capable of yielding permanently 200 cubic feet per second or more. Under present conditions, as a result of excessive draught, this volume of water can only be obtained at great cost by pumping from excessive depths. By permitting a restoration of the original storage in the artesian horizon, the majority of the wells would again flow at the surface, pumping could be dispensed with, and a great economic saving would result.

In connection with the use of artesian wells for public water supply, a similar condition sometimes pertains. A proper mode of procedure in such cases is to obtain an auxiliary source of supply adequate for present uses, allowing the artesian supply to rest for a period of years until restoration of the artesian horizon is accomplished. From then on, the artesian supply may be used as an auxiliary to meet increased water requirements, and so long as the draught does not exceed the available inflow to the intake area, the cost of procuring the water will be a minimum.

It is particularly to be noted that in general an artesian supply differs from a ground-water supply derived from shallow wells in the surficial ground-water zone, in that the intake area of artesian supply is fixed by natural conditions and does not vary with the draught from the ground-water horizon, whereas in the case of shallow wells in the surface zone, the infiltration area generally increases as the depth of depletion of the ground-water horizon increases by pumping. As a result, artesian supplies are likely to be lowered by excessive pumping more rapidly than surface ground-water supplies.

The continent of Australia consists of an arid interior basin, surrounded by mountain ridges. There are several great artesian horizons within this basin, the largest, at least, of which is of the interior type with artesian spring outlets. The extent to which agriculture can be carried on in Australia is determined by the water supply. A given number of sheep can be raised per miner's inch of available water. The yield of artesian bores in the Australian basins has gradually decreased since the utilization of these waters began.

The decrease in the yield of artesian bores may be due to various causes other than excessive draught.

(1) These causes include caving in of the bottom of the well, thus plugging the outflow pipe.

(2) Partial closing of the pores in the water-bearing bed, closely adjacent to the well, by silt.

(3) Leakage from the well into overlying non-artesian strata as a result of corrosion of the well casing.

While these conditions are all experienced in Australia, yet accurate measurements of the yield of hundreds of bores indicate that the average yield per well is decreasing at a rate of nearly 8 per cent per annum.

In the Los Angeles County artesian basin (figure 3) the area in which wells flow has decreased from an original extent of 150 square miles, to 105 square miles in 1904. In the Downey district there were more than 3000 wells in 1904, and in the adjacent Las Balsas District 300 wells. At that time a supply of 265 cubic feet per second was derived from pumped wells, and an estimated supply of 500 cubic feet per second was derived from flowing wells, making a total draught from the artesian horizon of some 750 cubic feet per second.

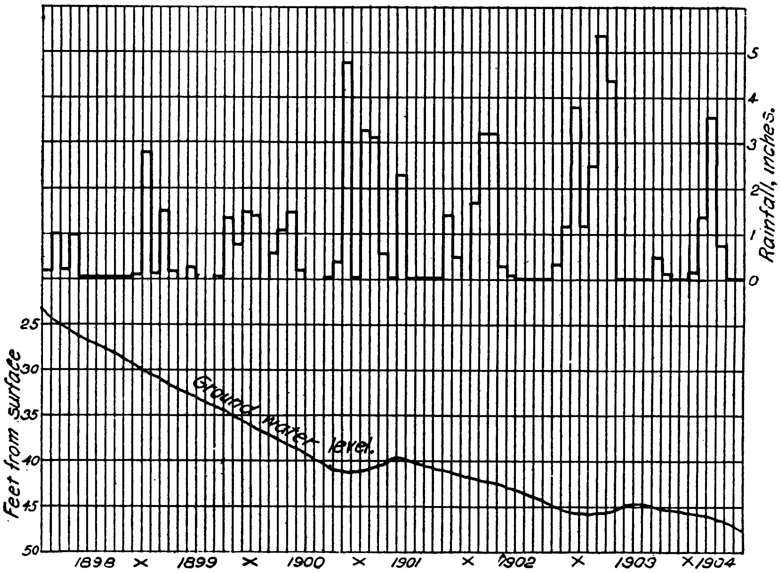


FIG. 4. VARIATION IN GROUND-WATER LEVEL NEAR ANAHEIM, CALIFORNIA (AFTER MENDENHALL)

Figure 4 shows the annual rainfall and ground-water level in the artesian horizon near Anaheim, Cal. In general the ground-water level has been lower at the end than at the beginning of each year, in spite of excessive rainfall in some seasons.

General depletion of ground water. Many persons believe that there has been a progressive dessication of streams, springs, and groundwater supplies since settlement in this country began. This is commonly attributed to the clearing of woodlands, which are popularly supposed to possess remarkable virtues as conservators of natural water resources. The determination of the effect of a cover of vegetation over the soil on ground water underneath is one of the most complicated and profound problems of hydrology.

It is not the intention here to go farther than to point out the uncertain foundation on which popular opinion is often based in such matters. During the summer season broad-leaved trees intercept about 25 per cent of the rainfall (Ref. 8). Natural herbaceous vegetation and cultivated crops intercept a smaller but still a considerable proportion of the rain falling on them. Clearing away the forests should, and undoubtedly would, increase the rain reaching the ground, and consequently the supply available for infiltration and repletion of ground water. There are other modifying factors.

Evaporation from the soil under forests or other vegetal cover is materially less than from bare ground. The opportunities for infiltration may be profoundly changed as a result of clearing and cultivation. In general the freedom of infiltration to the soil in a tilled field is greater than for any natural soil surface within woodlands or without, excepting bare shifting dune sands. Drainage of swamps and subsoil waters which frequently accompanies clearing and tillage may, however, greatly decrease the amount of deep infiltration. As regards effect on springs and ground water, subsequent treatment of the land, whether by drainage and tillage, or otherwise, must be taken into account, as well as the effect of the removal of forests.

At the University of Wisconsin Prof. F. H. King found that ground water stood generally at a greater depth below surface underneath crops than under bare areas in the same field. This would be expected because of the relatively large amount of water derived from infiltration, which is returned to the air by vegetation through the process of transpiration (Ref. 4).

From an elaborate study of ground-water levels at wells in forests as compared with those in adjacent clearings, Ototzkij found in general a marked depression of ground-water levels underneath woods as compared with those in the same soils and geologic formations in adjacent clearings (Ref. 5).

On the other hand, the late Dr. W. J. Magee, of the U. S. Bureau of Soils, compiled statistics for 28,906 wells, distributed over the United States, from which he reached the remarkable conclusion that since settlement began there has been an average lowering of the surface ground-water table of the United States, outside of the irrigation region, of no less than 9 feet. After examining in detail the published data on which Magee's conclusion is based, the author feels unable to accept this result. The data were obtained by circular letters. Very naturally those holding the affirmative view would be most likely to reply. It is the remarkable instances of such phenomena which attract attention, and there is also a tendency in compiling such statistics towards "counting the hits, and forgetting the misses." From the published data, it appears that many of the affirmative answers are, after all, mere opinions, not based on any measurements whatever, and that as to many others, decrease of the depth of water in wells was probably due to silting up of wells, decreasing their inflow capacity, or their actual depth, or both.

When a well is first put down, the ground-water level is usually measured. If it is ever measured again, it is likely to be in time of extreme drouth, when there is fear of shortage. Thus the two measurements compared by the casual observer are most likely to be, one under original natural conditions, and a later one under conditions of extreme drouth.

The author does not feel that this problem is capable of a general answer for the whole country. What has happened in a particular locality may, however, probably be determined in most cases by a careful hydrologic study of the local conditions. It does not seem that there is evidence to warrant the commonly expressed fear that ground-water supplies will gradually disappear as time goes on.

In conclusion, experience shows extensive depletion of ground-water supplies in some instances over large areas. The analysis of well problems by Miller-Brownlie's method leads to results concordant with experience in such cases. This method depends on the assumption that the ground-water slope in the cone of influence approaches a minimum limit as depletion progresses, and that the supply to the well is derived from storage within this ultimate region of influence plus infiltration over the depleted area.

This differs from ordinary well-yield formulas in which, while it is assumed that there is a maximum limit of the cone of influence, the assumed limit is usually smaller than that used in the Miller-Brownlie method. In ordinary formulas, infiltration over the cone of influence is usually neglected, and it is assumed that the supply is derived from ground-water flow from outside the cone of influence. Both methods of analysis are based on convenient working hypotheses. Neither one completely replaces the other, but each has its special applications.

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